

Analysis of the Relationship Between Shallow Water, Flood, and Tsunami

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Abstract. Contemporarily, it is necessary to delve into the intricate connections between shallow water dynamics, flood events, and tsunamis, elucidating their pivotal role in disaster management and environmental studies. This study explores how shallow water conditions influence the behavior of floods and tsunamis through recent advancements, numerical modeling, and observational techniques. The framework of the study involves an examination of the fundamental concept of shallow water, its characteristics, and its influence on wave behavior, sediment transport, and coastal interactions. The study subsequently analyzes the interplay between shallow water and floods, emphasizing the rapid increase in water levels as floodwaters approach shallower areas, contributing to coastal inundation. Similarly, the investigation explores how shallow water dynamics amplify tsunami wave heights and impact, particularly in coastal settings with complex features. By employing advanced simulations and real-world data, the study substantiates the crucial role of shallow water in shaping flood and tsunami risks. While acknowledging limitations, the research concludes by underscoring the implications of these relationships for disaster preparedness, environmental protection, and community resilience. The study contributes to a comprehensive understanding of the profound effects of shallow water dynamics on catastrophic events and highlights the importance of factoring these dynamics into effective disaster management strategies.

Keywords: Shallow water dynamics; flood propagation; tsunami amplification; disaster resilience; coastal interactions.

1. Introduction

Shallow water environments, characterized by water depths much smaller than the wavelengths of fluid waves, play a crucial role in various natural and human-driven processes. These regions include coastlines, estuaries, river deltas, and continental shelves, where interactions between water, sediments, and land shape ecosystems and influence human activities. Coastal regions, being transition zones between land and sea, are susceptible to dynamic processes such as tides, waves, and currents. Understanding these processes is vital for coastal engineering, navigation, and the protection of coastal communities from hazards like storm surges and erosion. Shallow water dynamics also impact marine ecosystems by influencing sediment transport, nutrient dispersion, and species distribution, making it essential for sustainable coastal management [1-3].

In estuaries and river deltas, where freshwater and seawater mix, shallow water dynamics control the distribution of nutrients and sediments, affecting aquatic habitats and fisheries. Additionally, these regions often host major ports and urban centers, emphasizing the need to comprehend the complex interactions between water flow, sediment transport, and human activities [4, 5].

Continental shelves, the submerged extensions of continents, are economically significant due to their rich biodiversity and potential for oil, gas, and mineral extraction. Shallow water processes here influence the transport of nutrients and organic matter, supporting marine food webs and influencing global carbon cycles. Shallow water research has evolved with advancements in fluid dynamics, numerical modeling, and remote sensing technologies. Researchers employ numerical simulations to

model wave propagation, sediment transport, and water circulation, aiding in predicting coastal hazards and designing infrastructure. Remote sensing platforms, like satellites and drones, provide valuable data for monitoring water quality, bathymetry, and shoreline changes, enhancing our understanding of these environments [6].

Given the growing concerns about sea-level rise, climate change, and anthropogenic impacts, shallow water research has gained prominence. It helps in formulating strategies for coastal adaptation, habitat preservation, disaster mitigation, and sustainable resource management. By delving into the complexities of shallow water dynamics, scientists and engineers contribute to safeguarding both the natural environment and human societies that depend on these intricate ecosystems. Prior research has extensively investigated the influence of shallow water dynamics on flood and tsunami events [7-10]. In flood studies, shallow water regions, such as river floodplains and coastal areas, significantly impact flood propagation and inundation patterns. Research has shown that the interaction between shallow water depths and the surrounding topography can lead to rapid increases in water levels during heavy rainfall, exacerbating flooding risks [11]. Furthermore, studies have emphasized the need to accurately model shallow water flow dynamics to enhance flood forecasting and mitigation strategies [12]. In the context of tsunamis, shallow coastal waters play a pivotal role in wave propagation and amplification. The decrease in water depth as tsunamis approach shorelines causes wave energy to compress, leading to substantial wave height increases. Past research has underscored the importance of understanding shallow water effects in predicting tsunami impacts on coastal communities. Coastal features such as bays, estuaries, and reefs can focus and amplify tsunami waves, intensifying their destructive potential [7]. Recent advances in numerical modeling and remote sensing have expanded our comprehension of these phenomena. High-resolution simulations coupled with accurate bathymetric data have improved flood and tsunami predictions by considering shallow water dynamics in intricate detail. Satellite observations provide invaluable insights into water level changes and inundation extents during extreme events. In conclusion, previous studies highlight the critical role of shallow water regions in shaping the outcomes of floods and tsunamis. Understanding the intricate interactions between water depth, topography, and wave behavior is essential for effective disaster preparedness, early warning systems, and resilient infrastructure planning in flood-prone and coastal areas.

The dynamic interplay between shallow water, flood events, and tsunamis is of paramount importance in disaster management and environmental studies. This study aims to comprehensively analyze the relationship between shallow water and these catastrophic events, shedding light on their intricate connections. By investigating recent advancements, numerical modeling, and observational techniques, this research seeks to enhance our understanding of how shallow water conditions influence the behavior of floods and tsunamis. The framework of this study revolves around comprehensively unraveling the intricate relationships between shallow water, flood events, and tsunamis. Beginning with an exploration of the basic concept and definition of shallow water, the study delves into its characteristics. Subsequently, it analyzes the role of shallow water in influencing the propagation and impact of floods, utilizing recent post-2015 literature and supporting data. A parallel investigation is conducted for tsunamis, elucidating how shallow coastal waters significantly shape tsunami wave behavior and effects. Acknowledging the study's limitations and future prospects, the research concludes by encapsulating the profound implications of these relationships for disaster management, environmental protection, and community resilience.

2. Basic Descriptions of Shallow water

Shallow water is a fundamental hydrodynamic condition that holds crucial implications for understanding various natural phenomena and human activities. It refers to aquatic environments in which the water depth is considerably smaller than the wavelengths of fluid waves, creating distinctive dynamics that significantly influence wave behavior, sediment transport, and the interactions between water and landforms. This concept finds relevance in a multitude of settings,

including coastlines, river floodplains, estuaries, and continental shelves [4, 5]. One of the key characteristics of shallow water is its capacity to alter the behavior of fluid waves. As waves approach shallower depths, their speed decreases, and their height increases, leading to wave shoaling. This phenomenon is pivotal in coastal zones, where wave energy becomes concentrated, often resulting in wave breaking along the shore. The interaction between shallow water and underlying topography influences the direction and speed of currents, sediment movement, and coastal morphology. These factors contribute to the intricate balance of coastal ecosystems and impact coastal communities. The notion of critical depth is closely tied to shallow water conditions. Critical depth occurs when the water depth equals the wave base—the depth at which water particles are influenced by wave motion. This depth demarcation greatly affects wave behavior. Below the critical depth, waves experience reduced energy due to seafloor interaction, leading to altered wave dynamics. Conversely, above the critical depth, waves exhibit surface behavior with minimal seafloor influence.

Shallow water dynamics have profound implications for scientific research and practical applications. In the realm of coastal engineering, a deep understanding of shallow water behavior is essential for predicting storm surges, erosion patterns, and sediment transport. In hydrology, recognizing shallow water conditions is crucial for flood prediction, river management, and water resource planning. Moreover, as tsunamis approach coastlines, the shallow water effect amplifies wave heights, significantly impacting the devastation caused by these catastrophic events. Modern advancements in technology and numerical modeling have revolutionized the study of shallow water. High-resolution simulations coupled with accurate bathymetric data enable accurate predictions of wave behavior and sediment transport in shallow water regions. Remote sensing platforms, such as satellites and drones, provide valuable insights into shallow water dynamics, offering a comprehensive view of coastal changes, water levels, and shoreline shifts [3].

In conclusion, shallow water constitutes a fundamental hydrodynamic condition with far-reaching implications for understanding fluid dynamics, wave behavior, and coastal processes. Its influence extends to various aspects of science, engineering, and disaster management. Grasping the dynamics of shallow water is integral for accurately predicting the behavior of waves, floods, and tsunamis in coastal and estuarine regions. This understanding not only enriches our scientific knowledge but also contributes to safeguarding coastal communities and preserving delicate ecosystems in the face of changing environmental conditions.

3. Relationship with Flood

The relationship between shallow water dynamics and flood events is integral to understanding the propagation and impact of floods, especially in coastal and low-lying areas. Shallow water regions, characterized by their limited water depths, significantly influence the behavior of floodwaters and can exacerbate the effects of heavy rainfall and storm surges. As floodwaters approach shallower depths, such as those found in coastal plains or river floodplains, the interaction with the underlying terrain becomes pronounced. This interaction can lead to rapid increases in water levels, particularly during intense rainfall events. Fig. 1 illustrates this phenomenon, where the water surface rises rapidly as it approaches shallower areas, causing flooding along the coastline. This elevation of water levels can result in inundation of nearby communities and infrastructure.

Moreover, the interaction between shallow water conditions and floodwaters is particularly evident during storm surges, which occur when powerful coastal storms push seawater onto land. In shallow coastal regions, the shallowness amplifies the surge's impact by restricting the surge's ability to disperse and dissipate energy. This amplification effect can lead to severe flooding in coastal communities. Recent studies have employed advanced numerical simulations and field observations to analyze the intricate relationship between shallow water dynamics and flood events. These studies have demonstrated how water depth, topography, and precipitation patterns in shallow water regions influence flood propagation and inundation extents. Incorporating real-world data, these investigations underscore the significant role of shallow water conditions in shaping flood risks.

In conclusion, the relationship between shallow water dynamics and flood events is characterized by the rapid rise in water levels as floodwaters approach shallower depths. The influence of shallow water is particularly pronounced during storm surges and heavy rainfall events, amplifying the impact of flooding in coastal and low-lying areas. By understanding the interplay between water depth and flood behavior, communities and policymakers can better prepare for and mitigate the impacts of flooding events.

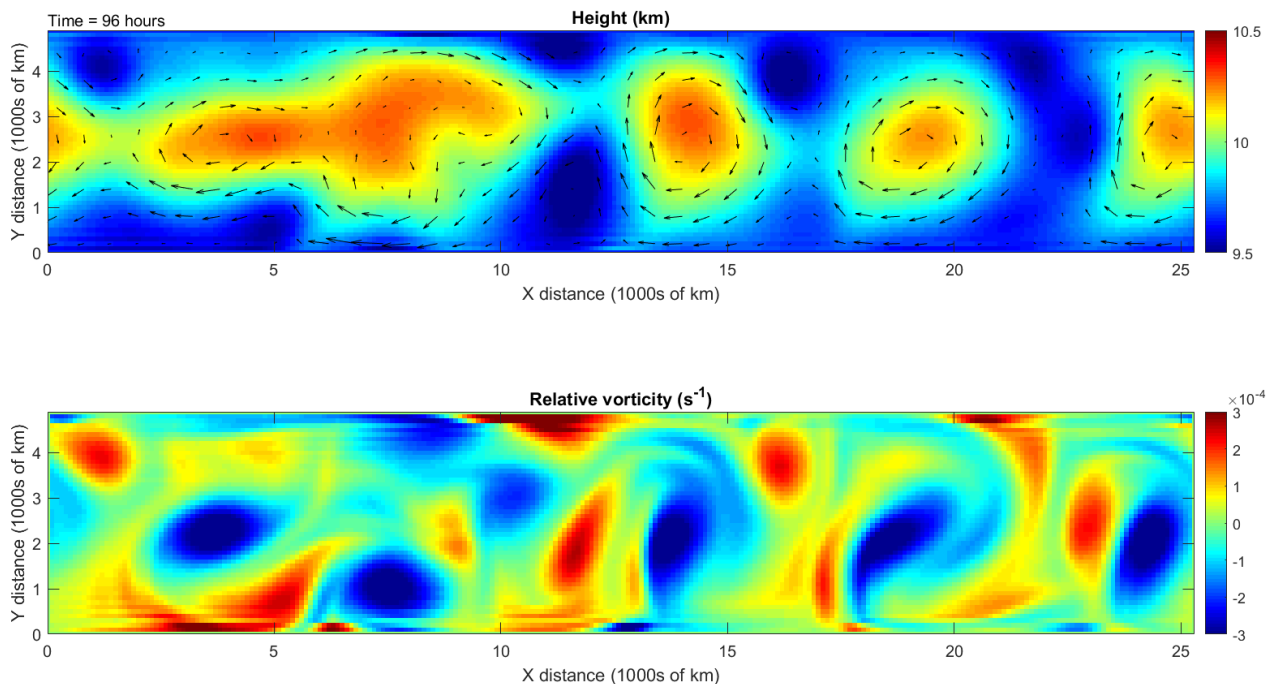


Fig. 1 Illustration of the interaction between shallow water dynamics and floodwaters. The rapid increase in water levels in shallower areas contributes to coastal flooding during heavy rainfall events.

4. Relationship with Tsunami

Shallow water regions play a pivotal role in influencing the behavior and impact of tsunamis, which are large and devastating sea waves often triggered by undersea earthquakes. Tsunamis are characterized by their long wavelengths, making them particularly susceptible to the effects of shallow water dynamics [9-11]. When a tsunami wave approaches shallower coastal waters, its interaction with the seabed and the decrease in water depth lead to a phenomenon known as wave shoaling. The energy that was spread out over a large area in deep water becomes compressed into a smaller space, resulting in a significant increase in wave height. This compression effect is illustrated in Fig. 2, where the initial Gaussian shape of the wave transforms into a much higher wave crest upon approaching shallow waters. The initial Gaussian shape can be associated with the displacement caused by seismic events, although it is exaggerated in magnitude for visualization purposes [8].

Moreover, the amplification of tsunami wave heights in shallow water regions can lead to devastating consequences for coastal communities. Areas with intricate coastal features like bays, estuaries, and inlets can further enhance wave energy concentration, intensifying the impact of tsunamis. Historical tsunamis, such as the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami, vividly demonstrate how the interplay between shallow water dynamics and tsunami waves led to catastrophic inundation and destruction along coastlines.

To substantiate this relationship, recent research studies employ numerical simulations and real-world data to analyze the effects of shallow water on tsunami propagation. These studies showcase how the energy redistribution in shallow water regions significantly alters tsunami wave behavior and highlights the critical role of accurate bathymetric data in predictive modeling.

In summary, the relationship between shallow water dynamics and tsunamis is characterized by wave shoaling, which leads to the compression and amplification of tsunami wave energy as they approach coastal shallows. This phenomenon underscores the significance of considering shallow water effects in tsunami prediction, preparedness, and mitigation strategies, as the interaction between these factors can dramatically shape the destructive potential of tsunamis.

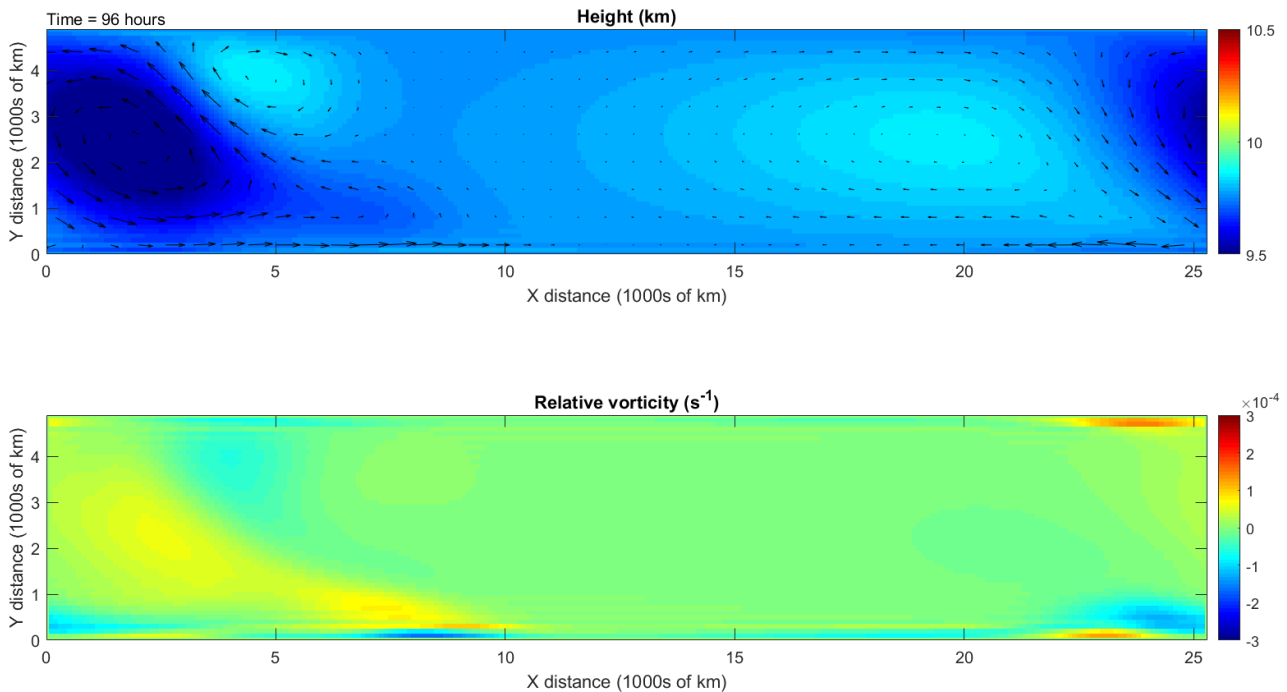


Fig. 2 Illustration of wave shoaling in shallow waters. The initial Gaussian shape (blue) transforms into a higher wave crest (red) due to the compression effect as the wave approaches shallower depths.

5. Limitations and Prospects

While this study has provided valuable insights into the intricate relationships between shallow water dynamics, flood events, and tsunamis, it is important to acknowledge certain limitations that may influence the comprehensiveness of the analysis. One key limitation lies in the complexity of the natural systems under consideration. Shallow water regions, floods, and tsunamis are influenced by a multitude of factors, including topography, meteorological conditions, and sediment characteristics. The interplay of these variables is intricate and can lead to nonlinear behaviors that are challenging to capture accurately in predictive models. Additionally, while this study aims to provide a holistic overview, there may be regional variations and unique geological features that could impact the relationships between shallow water dynamics and catastrophic events. The specific characteristics of coastlines, river systems, and undersea geological structures can lead to nuanced effects that are beyond the scope of a generalized analysis.

Looking ahead, several promising avenues for future research and applications emerge from this study's findings:

- **Enhanced Predictive Models:** Future research could focus on refining numerical models that account for a broader range of influencing factors, including sediment transport, vegetation, and human-made structures. Incorporating these complexities into models can yield more accurate predictions of flood and tsunami impacts in shallow water regions.
- **Interdisciplinary Approaches:** Collaborations between researchers from various disciplines such as geology, oceanography, and engineering can lead to a more comprehensive understanding of the relationships between shallow water dynamics and catastrophic events.

Integrating diverse perspectives can result in more holistic predictive models and mitigation strategies.

- **Real-Time Monitoring and Early Warning Systems:** Advancements in remote sensing technologies offer opportunities to establish real-time monitoring systems that provide continuous data on water levels, wave behavior, and coastal changes. Such systems could contribute to more effective early warning systems for floods and tsunamis in shallow water areas.
- **Climate Change Considerations:** As sea levels rise due to climate change, the influence of shallow water dynamics on flood and tsunami events may become even more pronounced. Future research should explore how changing environmental conditions interact with shallow water effects and their implications for disaster resilience.
- **Community Engagement and Preparedness:** The findings of this study can inform community education and preparedness efforts. Raising awareness about the impacts of shallow water on floods and tsunamis can empower communities to develop adaptive strategies, emergency plans, and sustainable development practices.

In conclusion, while this study's analysis of the relationship between shallow water, flood events, and tsunamis has shed light on critical connections, inherent limitations and regional variations remind us of the complexity of these interactions. Future research holds the potential to refine models, adopt interdisciplinary approaches, and leverage advanced technologies to enhance predictive capabilities and disaster management strategies in shallow water regions. By addressing these limitations and embracing future outlooks, researchers and stakeholders can contribute to more resilient and informed coastal communities.

6. Conclusion

To sum up, this study intricately examines the relationships among shallow water dynamics (SWD), flood events (FE), and tsunamis. The interplay between SWD, FE, and tsunamis underscores the significant influence of water depth. Investigating SWD's impact on flood propagation and tsunami effects reveals its vital role. Integrating SWD dynamics into predictive models and disaster management strategies is essential for enhancing preparedness and resilience.

Author Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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